Taylor & Francis
Taylor & Francis Group

Machining Science and Technology
An International Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/lmst20

Experimental comparison of the indexable drilling with different U drills on hole quality

Aslan Akdulum & Yunus Kayir

To cite this article: Aslan Akdulum & Yunus Kayir (29 Nov 2023): Experimental comparison of the indexable drilling with different U drills on hole quality, Machining Science and Technology, DOI: 10.1080/10910344.2023.2286658

To link to this article: https://doi.org/10.1080/10910344.2023.2286658


Published online: 29 Nov 2023.


Submit your article to this journal


Article views: 51


View related articles


View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=lmst20

MACHINING SCIENCE AND TECHNOLOGY
https://doi.org/10.1080/10910344.2023.2286658

Taylor & Francis
Taylor & Francis Group

Check for updates

Experimental comparison of the indexable drilling with different U drills on hole quality

Aslan Akdulum[a] and Yunus Kayir[b]

[a]Department of Machinery and Metal Technologies, Başkent OSB Vocational School of Technical Sciences, Hacettepe University, Ankara, Turkey; [b]Faculty of Technology, Department of Manufacturing Engineering, Gazi University, Ankara, Turkey

ABSTRACT

U drills are estimated to account for around 53% of all drilling equipment's market share. This study compared and contrasted the impacts of the balance angle, the U drill length/diameter ratio, and the extra coolant hole opened in the chip evacuation channel on the hole quality when drilling AA 7075-T651 material. Hole quality was investigated by deviation from diameter, deviation from circularity, deviation from cylindricality, surface roughness, forces, and torque. Three cutting speeds, three feed rates, and four distinct U drills were chosen as input parameters. The studies revealed that when the U drill's length/diameter ratio increased, the hole quality deteriorated. The best hole quality was nonetheless achieved by the tool with the additional coolant hole. The higher balance angle resulted in improved hole quality. However, it was discovered after looking at the chips and inserts that the chatter only happened while drilling with a U drill that had an additional coolant hole. While the extra coolant hole opened to the chip evacuation channel, it affected the hole quality positively but caused chatter, which negatively affected the inserts. The reasons for these results are discussed in detail.

KEYWORDS

U drill; deviation from diameter; deviation from cylindricality; deviation from circularity; surface roughness

Introduction

One of the most preferred 7xxx series aluminum-magnesium-zinc alloys in the field of aviation is the 7075 alloy (Totten and MacKenzie, 2003). By creating precipitates in the structure, the T651 aging process is used to enhance the mechanical characteristics of the alloy (ASM International Handbook Committee, 1992). In addition to aviation, 7075 aluminum alloy is extensively utilized in many different industries due to its low density and good mechanical qualities (Paktinat and Amini, 2017; Yaşar, 2019). Drilling plays a significant role in the industries that utilize this material (Li et al., 2020). When all machines are considered, it is predicted that the

CONTACT Aslan Akdulum a.akdulum@gmail.com Department of Machinery and Metal Technologies, Başkent OSB Vocational School of Technical Sciences, Hacettepe University, Ankara, Turkey.

© 2023 Taylor & Francis Group, LLC

ratio of drilling operations to all metal cutting operations is 36%, and when CNC machines are included, it is 40% (Astakhov, 2014).

In almost all of the investigations where 7075 aluminum alloy was drilled, a helical drill was employed. Margin, chisel edge, and cutting edges wear out after certain repetitions of drilling with a helical drill (Xiang et al., 2018). In addition, drilling holes directly is not possible due to the helical drill's increased diameter. Because as the drill diameter increases, the drill chisel edge also gets larger. On the other hand, the increased chisel edge generates a wandering motion rather than cutting at the first point of contact with the component, which increases cutting forces and temperature and results in an abnormally quick fall in hole quality (Ralph et al., 2006). With the increase in drilling forces and temperature, the tool life is negatively affected, the drill wears out, and the drill needs to be sharpened. In fact, if wear occurs on the margin, the drill may become completely unusable due to its solidity (Zhu et al., 2018). To overcome this problem, the front hole is drilled (Yagmur and Muharrem, 2021). Pre-drilling requires the use of a larger number of cutters. Thus, time is wasted, and an additional negative cost occurs.

To get beyond the aforementioned issues while drilling large-diameter holes (12 and above), one of the modern cutting tools is the indexable insert drill (U drill). According to estimates, U drills account for 53% of drilling instruments and 8% of the overall market for cutting tools (Parsian, 2018). It can drill larger diameters of solid materials in less time at a higher feed rate and cutting speed (Svensson, Andersson, and Andersson Lassila, 2022). U drills have quite different features from helical drills. U drills do not have a chisel edge; instead, they have two indexable inserts, one in the center and one on either side, and a separate material serves as both the body and the insert (Wang, Venkatesh, and Xue, 1991). Therefore, drilling parameters and output responses have different dynamics compared to a helical drill. There are a number of drawbacks to using the U drill over the helical drill, especially with regard to the hole quality. These disadvantages are higher circularity deviation (Rahman, Seah, and Venkatesh, 1988), worse surface roughness (Nieslony et al., 2017), higher thrust force, and higher temperature values (Okada et al., 2014) in materials such as AISI 304 and AISI 1045. Poor hole quality is time-consuming and costly, as it requires secondary operations such as enlargement, boring, and reaming (Venkatesh and Xue, 1996). To enhance the hole quality when drilling aluminum alloys with U drills, several experiments have been carried out. In these studies, Heisel and Schaal examined the burr heights by drilling the AA 2007 material with different cooling methods. When compared to dry machining with the least amount of lubricant, burr height is almost negligible (Heisel and Schaal, 2009). Biermann and Hartmann

drilled the AA 6082 material to examine the effects of different coolant methods. They found that cooling methods did not have a positive effect on deviation from diameter and circularity (Biermann and Hartmann, 2012). Kaymakçı et al. created an analytical forecasting model. Thrust force and lateral forces for the AA 7050-T7451 material were consistent with the findings of the experiments. However, before using a U drill to drill, they drilled a pilot hole to remove the central insert's penetrating impact (Kaymakci, Kilic, and Altintas 2012). Pre-drilling is not recommended as it causes unbalanced lateral forces and chatter due to the different radial distances of the inserts of the U drills (Parsian, 2018). In the analytical prediction model created by Kılıç and Altıntaş, AA 7075 material was drilled without pre-drilling. As a result, the prediction error in lateral forces was 38%, and the prediction error in thrust force increased to 60%. This inaccuracy was attributed to issues brought on by the drill's very low cutting speed close to its axis of rotation and the central insert's indentation effect (Kilic and Altintas, 2016). Akdulum and Kayir's study looked at the thrust force, torque, and spindle load, and it was found that varying U drill lengths had an impact on the output responses (Akdulum and Kayir, 2023). In a second investigation, they examined the thrust force, torque, and surface roughness using Taguchi, ANFIS, and ANN to corroborate the impact of various U drills (Akdulum and Kayir, 2023). In another study, optimum machining parameters were determined with GRA by examining forces, sound signals, and spindle load (Akdulum and Kayir, 2023). When previous studies are examined in detail, the effect of drilling aluminum alloys with U drills on hole quality has not been investigated in depth or comprehensively. U drill product development and research studies are still ongoing in industry and academia. In this respect, U drills need to be further investigated in order to use them more efficiently and obtain the desired quality of holes.

In order for a hole to have the desired tolerance and quality, the dimensional tolerance (hole diameter), shape tolerance (circularity, cylindricality), and surface roughness must be within the desired ranges (Sheth and George, 2016). Control of output responses such as circularity and cylindricity increases fastener life, while a lack of control reduces life by causing fatigue and increasing assembly time (Varatharajulu et al., 2021). In this respect, strict control of tolerance values is important (Sheth and George, 2016). There are several ways to obtain the appropriate tolerances and hole quality, including employing various drills or ultrasonic vibrations (Sun et al., 2023). Additionally, the right choice of drilling parameters results in a better-quality hole, optimal drilling forces, and a more effective drilling operation (Astakhov, 2014). In past research on the drilling of aluminum alloys with U drills, the significance of the drilling parameters and their

impact on hole quality were not sufficiently covered. It is necessary to determine the appropriate drilling parameters (feed rate and cutting speed) for the selected insert. Hole quality is directly impacted by the optimal parameters. To counteract chatter and imbalanced radial forces brought on by inserts situated at various radial distances and angles, U drills have a balance angle between the central insert and the peripheral insert (Jochem, 2006). This balance angle has a direct effect on hole quality. However, no research has looked into how this balance angle affects hole quality. For U drills with the same nominal diameter but various lengths, the balance angle varies. U drills with various length/diameter ratios ought to be chosen for this purpose. Additionally, the maker of some U drills drills a third coolant hole in the chip evacuation channel where the center insert is located in order to improve the hole quality through effective cooling. However, it remains to be seen what effect this extra hole has on hole quality.

This study intends to examine the impact on hole quality of indexable drilling AA 7075-T651 material with various U drills. It is aimed at investigating the shortcomings mentioned in the literature. Four different U-drills were selected to investigate these shortcomings. Except for the nominal diameter and identical inserts, all U drills are different from each other. In order to compare how different U drills and drilling parameters affect hole quality, output responses were calculated. These output responses are deviation from diameter, deviation from circularity, deviation from cylindricity, surface roughness, and drilling forces (F_x, F_y, F_z, and M_z). This investigation is intended to fill a knowledge gap with indexable drilling of aluminum alloys. This study is interesting in that it compares the effects of various length/diameter ratios, balance angles, and extra cooling holes in U drills on the hole quality (deviation from diameter, circularity, cylindricity, and surface roughness).

Material and method

For the experimental study, AA 7075-T651 material was prepared and used in $40 \times 40 \times 40$ mm dimensions. At least three measurements of the hardness and an examination of the spectrum were made, and the average was taken. The average hardness of the material was found to be 172 Brinell. The substance's chemical composition, as determined by the spectrum analysis, is shown in Table 1.

Table 1. The chemical make-up of AA 7075-T651: % by weight.

Si	Fe	Cr	Mn	Ti	Zn	Cu	Mg	Al
0.11	0.18	0.2	0.08	0.03	5.6	1.7	2.6	Balance

A Johnford VMC-850 brand CNC machine tool was used for the tests. The spindle has a 7.5 KW spindle power, a maximum spindle speed of 8000 rpm, and a measurement accuracy of 0.001 mm. The operating system is Fanuc. Water and 5% semi-synthetic cutting and cooling fluid were combined to create an emulsion that was used for cooling. Through-hole and standard-hole drilling techniques were used in the drilling trials. The cooling liquid is configured to be sprayed into the cutting medium from the outside, just like the experimental setup in Figure 1 does.

The experiments utilized four distinct U drills. Except for two, all U drills have a nominal diameter of 20 mm and vary in length. As seen in Figures 2 and 3, one U drill with the same nominal diameter and length (Tool 3) has an additional cooling hole in the chip evacuation channel where the center insert is situated, whereas Tool 2 does not. Both the peripheral insert and the central insert are positioned behind the normal cooling holes that were opened on the U drill body. The cutting area where the cutting edge and the workpiece come into contact is not directly penetrated by the coolant sprayed through these holes. As the cutting speed approaches zero at the hole center, larger forces and therefore higher temperatures are more likely to occur at the hole center, that is, at the central insert. Therefore, it is thought that an extra third cooling hole was opened in order to directly cool the area where the central insert comes into contact with the workpiece. In this way, it may be considered to reduce cutter wear by preventing heat generation in a relatively closed hole. Since the cutting zone will be cooled directly, it is thought that Tool 3 causes a more effective decrease in cutting temperature. The dimensions of the U drills used in the tests are listed in Table 2. The U drills were reverse engineered in three dimensions, modeled in the computer, and the values were measured to ascertain the balance angles of the U drills. In addition, the measured values were confirmed by measuring the images taken on the U drill

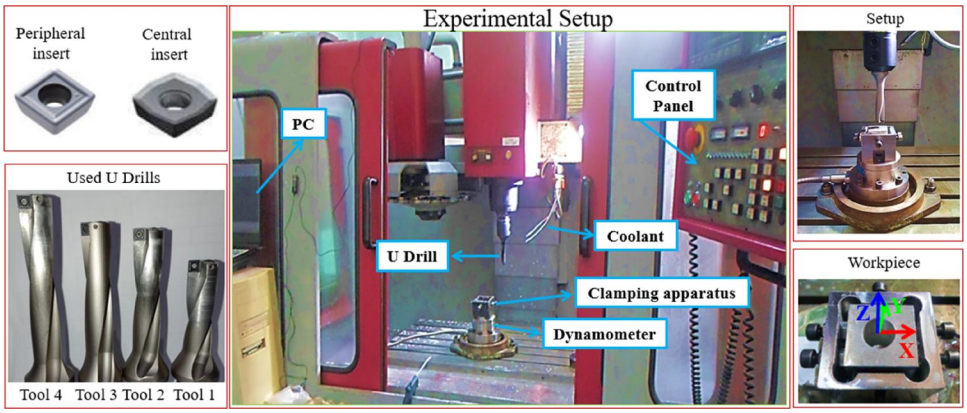


Figure 1. The experimental setup.

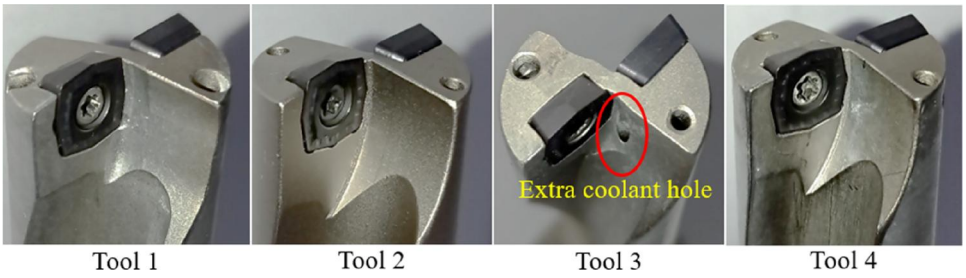


Figure 2. U drills used.

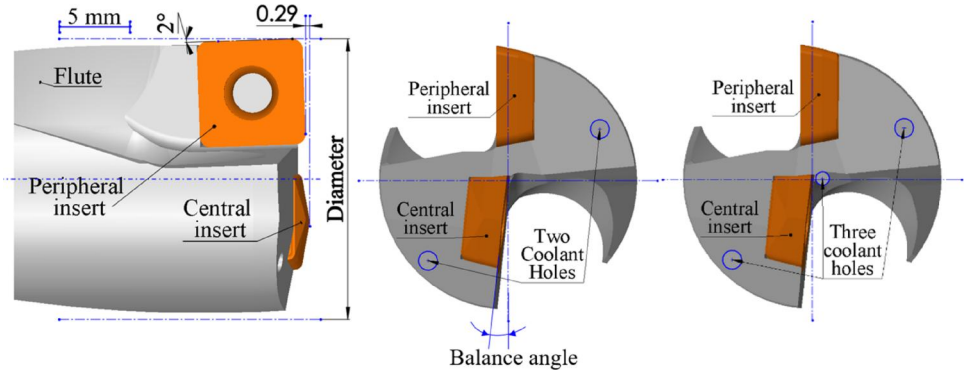


Figure 3. Schematic illustration of U Drill.

Table 2. U drill dimensions used.

U Drills	Diameter (D: mm)	Length (L: mm)	Number of internal cooling holes	Balance angle (°)
Tool 1	20	60	2	6.38
Tool 2		80	2	5.27
Tool 3		80	3	5.99
Tool 4		100	2	4.96

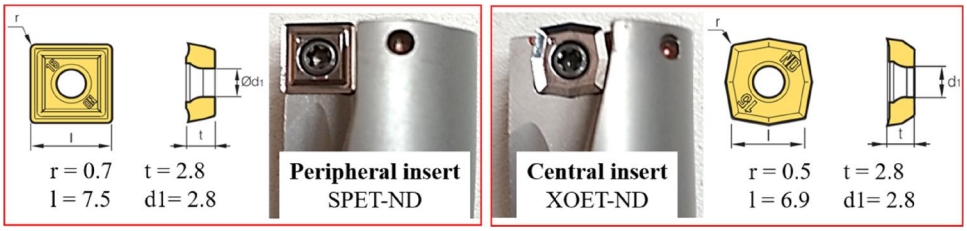


Figure 4. Cutting inserts and sizes.

with a microscope. In order to obtain more circular-shaped holes, radial forces must be balanced. In U drills, a balance angle must be placed between the central and peripheral inserts to balance the radial forces. This balance angle varies depending on the length and rigidity of the U drill.

The dimensions of the cutting inserts utilized are shown in Figure 4. In U drills, the central and peripheral inserts are typically used; however, they differ slightly. Due to the various cutting speeds and load conditions they

operate under, edge geometry and coating can alter (Ahmed and Kumar, 2016). Although the inner and outer inserts of the U-drill in this study have different geometrical features, both are uncoated tungsten carbide inserts that are suitable for cutting aluminum. The periphery inserts were made of SPET 07T208-ND geometry and H01-grade inserts, while the center insert was made of XOET 07T205-ND. We utilized U drills with similar inserts and the same nominal diameter. New inserts with the same properties were used for each drilling experiment. The cutting inserts were visually inspected with a USB microscope before the hole drilling test after being inserted into the U drill body. After ensuring that there was no problem, drilling experiments were carried out. In addition, all U drill bodies were supplied by the same manufacturer and used during the same experiment. Thus, an attempt was made to compare all U drill bodies in detail under identical conditions.

The U drill is attached to the spindle using a tool holder of the veldon type, model BT 40 VT 25 90. The suggested drilling parameters were taken into consideration while producing the cutting tool catalog proposals. The feed rate and cutting speed figures were computed using the cutters' catalog information. With the help of preliminary tests, the suitability of the chosen drilling parameters was evaluated, and the chosen drilling parameters were then chosen. A clamping apparatus was designed to properly fasten the workpiece before drilling experiments. After the workpieces were connected, the connection suitability was checked with a dial indicator. In the selection of U drills, the length-to-diameter ratios (3D, 4D, and 5D), which are common among different manufacturers on the market, were preferred. 4D cutters that are currently available on the market were chosen in order to compare the effects of the additional coolant hole. Experiments were carried out according to the full factorial experiment principle ($4 \times 3 \times 3$). The drilling variables are listed in Table 3.

An experimental setup was prepared to measure the forces and hole quality. With the experimental setup, forces (thrust force, lateral forces, and torque) were measured during drilling, and hole quality measurements were made afterwards. Using a Kistler 9272 dynamometer and a Kistler 5070 A amplifier, axial and lateral forces were obtained. Experiments were carried out at a sampling frequency of 100 Hz. A Hexagon brand coordinate measuring machine (CMM) with a measuring range of 1 µm was used

Table 3. Used drilling parameters.

U Drills	Feed rate, f (mm/rev)	Cutting speed, V_c (m/min)
Tool 1	0.06	200
Tool 2	0.09	250
Tool 3		
Tool 4	0.12	300

to measure deviation from diameter, circularity, and cylindricality, and Pc-dmis CAD ++ 2014 was used as a computer program. For a more detailed measurement in the current study, three planes, 5, 20, and 35 mm below the hole entrance, were created as shown in Figure 5. By using the probe to scan the inside wall surface of the hole in a 360° motion, measurements were taken in these planes. The clamping device used during drilling is preferred to secure the workpiece to the CMM workstation.

All drilled workpieces had their surface roughness measurements taken inside the holes. The "Mahr Perthometer M1" type surface roughness instrument shown in Figure 6 was used for the measurements. By performing the measurements three more times from each of the four sides and measuring 5 mm inside the hole from both the entry and the exit, the arithmetic average was calculated. The arithmetic mean was used to calculate the mean surface roughness value. The device's measuring methods were discovered to be the tracer tip method, with a cutoff of 0.8 mm, a scanning length of 5.6 mm, and a scanning speed of 0.5 mm/s. Minitab 19 and the Microsoft Excel program were used to take the averages and draw the graphs.

Results and Discussion

Different U drills' effects on hole quality

Hole quality is very important, especially for holes drilled for assembly purposes (Sheth and George, 2016). The hole diameter must be within tolerances, and the geometric shape (circularity or cylindricality) must be appropriate (Ahmed and Kumar, 2016). Inappropriateness causes problems in the assembly process and reduces functional service life (Uddin et al., 2018). This situation causes great negativity in terms of time and finances

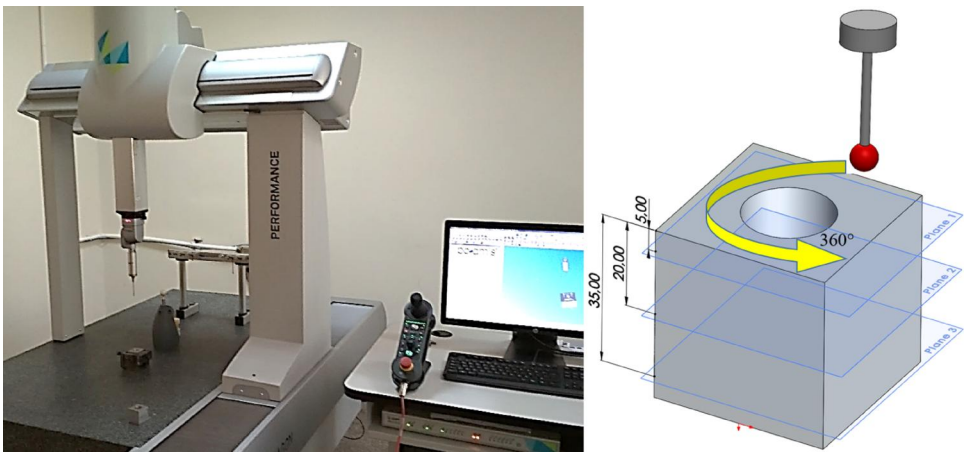


Figure 5. CMM measuring setup.

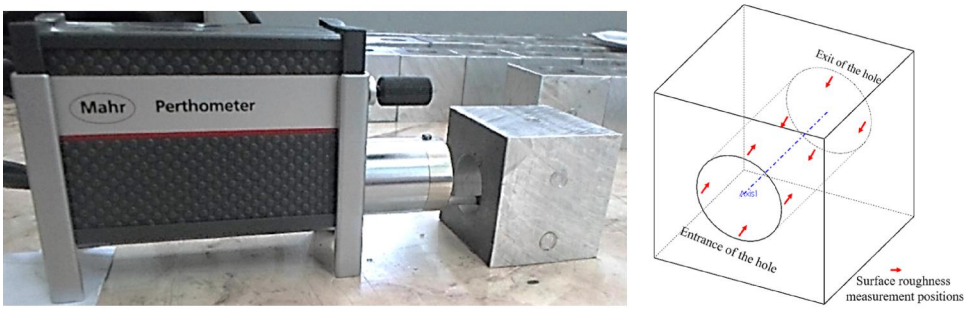


Figure 6. In-hole roughness measurement.

(Giasin et al., 2016). Aluminum alloys have a natural tendency to bond to the surface of the hole and the cutting tool. For the purpose of processing aluminum material, insert grades are created to help lessen this tendency. However, changing the insert quality alone is not enough. In cutting tools such as U drills, the U drill body also has significant effects on the hole quality. Because drilling takes place in a somewhat enclosed space, the chips that are ejected through the hole adhere to the tool and the surface of the hole. Thus, hole quality may be negatively affected. Therefore, in the design of U drill bodies, parameters such as balance angle, coolant hole, and helical channel design must be taken into consideration. The quality of the holes will be greater if less workpiece material and chip adhere to the tool during the machining process. Therefore, there is a direct relationship between tool surface and hole quality. Within the framework of this study, the modifications in hole quality brought on by U drills with various attributes were experimentally evaluated and compared. Nine experiments with each U drill were carried out according to the full factorial experiment principle, and their averages were taken. Figure 7 was obtained with the averages obtained. Figure 7a displays the diameter deviation when compared to U drills; Figure 7b shows the deviation from circularity; Figure 7c shows the deviation from cylindrical shape; and finally, Figure 7d compares the values for surface roughness. The worst values were obtained with Tool 4, which had the largest length-to-diameter ratio. Tool 3 with the extra coolant hole results in 80.6% less diameter deviation, 10% less circularity deviation, 55.8% lower cylindrical deviation than Tool 2 without the extra coolant hole, and 11.5% lower surface roughness. With the exception of Tool 3, deviations from diameter, circularity, and cylindricality grew as the length/diameter ratio increased. Except for Tool 4, the values for surface roughness and deviation from circularity were quite similar and did not differ significantly. Surface roughness values were relatively high. It can be said that the peripheral rake angle of the U drill is 0° (excluding the chip breaker). In a study conducted in the literature, negative rake angle causes higher surface roughness than positive rake angle in machining aluminum

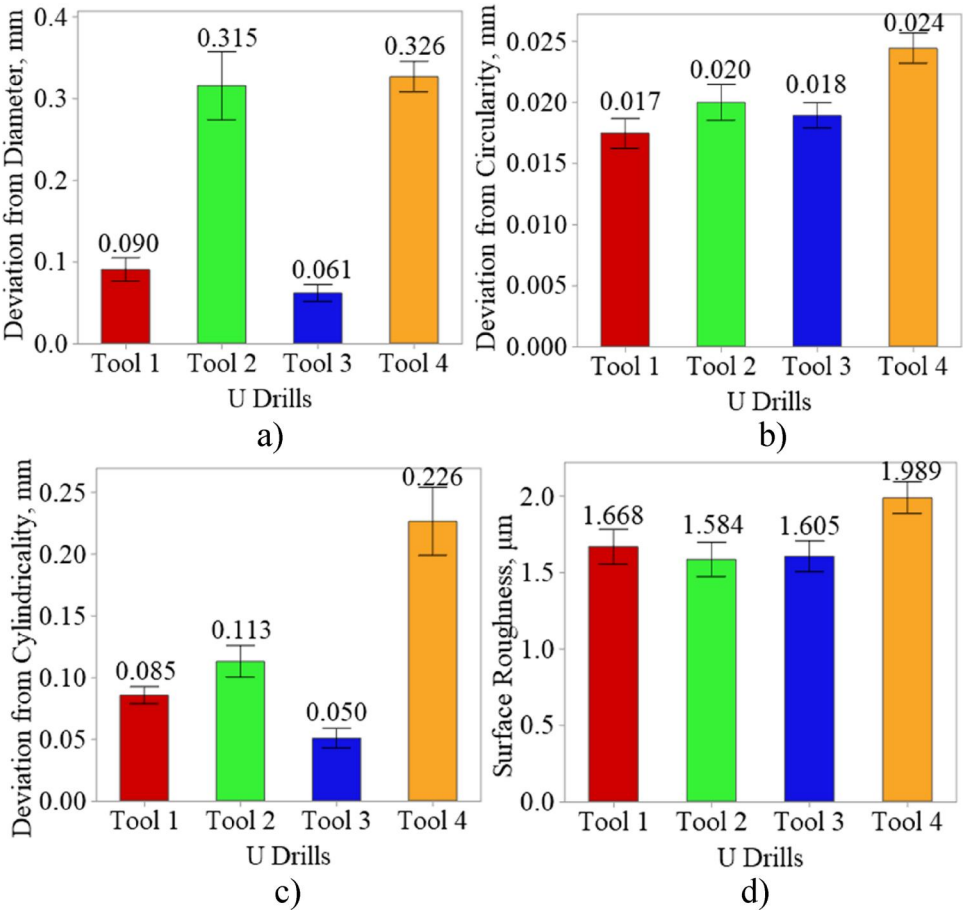


Figure 7. The impact of different U drills on the hole's integrity.

materials (Sekmen, Günay, and Şeker, 2015). The shear plane angle drops, and thicker chips emerge when the rake angle is negative relative to the positive rake angle (Bayraktar and Çamkerten, 2020). More force is required to deform thicker chips, and therefore the surface roughness is adversely affected (Aydin and Ozcatalbas, 2003).

With the increase in the length/diameter ratio, the hole quality (diameter deviation, deviation from circularity, deviation from cylindricality, and surface roughness) values tended to increase. The extra coolant hole in Tool 3 unexpectedly improved the hole quality, resulting in the lowest values out of circularity deviation. Even with standard drilling conditions, the natural frequency of the cutting tool drops with length, reaching the resonance frequency, and high-amplitude vibrations may ensue (Yaman,Bicakci, and Ozgedik, 2017). These vibrations cause deviations from dimensional and geometric tolerances (Nouari et al., 2005). Additionally, it is hypothesized that the extra cooling hole created on the body of the U drill compromises body stiffness and results in dynamic instabilities. It has been stated in

various studies that the increase in dynamic instability will cause tool deviations and cause negativity in hole geometries and hole quality (Bahçe and Özdemir, 2019). In addition, the adhesion of the chips that occur in the drilling of aluminum alloys to the U drill chip evacuation channel also causes problems in hole quality (Biermann and Hartmann, 2012). The chip evacuation channels of the U drill that are not in the same geometric dimensions, asymmetrical insert placement, and the presence of the coolant hole in the body can also cause vibrations and tool deviations (Svensson, Andersson, and Andersson Lassila, 2022). In drilling, three types of vibration modes are more prominent: whirling, lateral, and torsion-axial (Yaman, Bicakci, and Ozgedik, 2017). The lateral, axial, and torsional tool deflections caused by these three vibration mode types are depicted in Figure 8. Lateral deviations break the tolerances of size and shape (Ahmadi and Altintas, 2013). It is evaluated that the vibrations of the U drill increase with the increase in the length/diameter ratio, except for Tool 3, so that higher output responses may have occurred by increasing the lateral deflection (Arvajeh and Ismail, 2006; Abele and Schäfer, 2013).

The central insert of Tool 3 has an additional coolant hole inserted by the manufacturer in the chip discharge channel. It is believed that the third cooler hole was opened in order to deliver a more concentrated amount of coolant to the cutting environment, hence improving the cooling of the cutting region. However, this extra cooler hole created extra space on the body, contrary to the expected benefit, and caused the rigidity of Tool 3 to decrease compared to other U drills. The decrease in stiffness resulted in

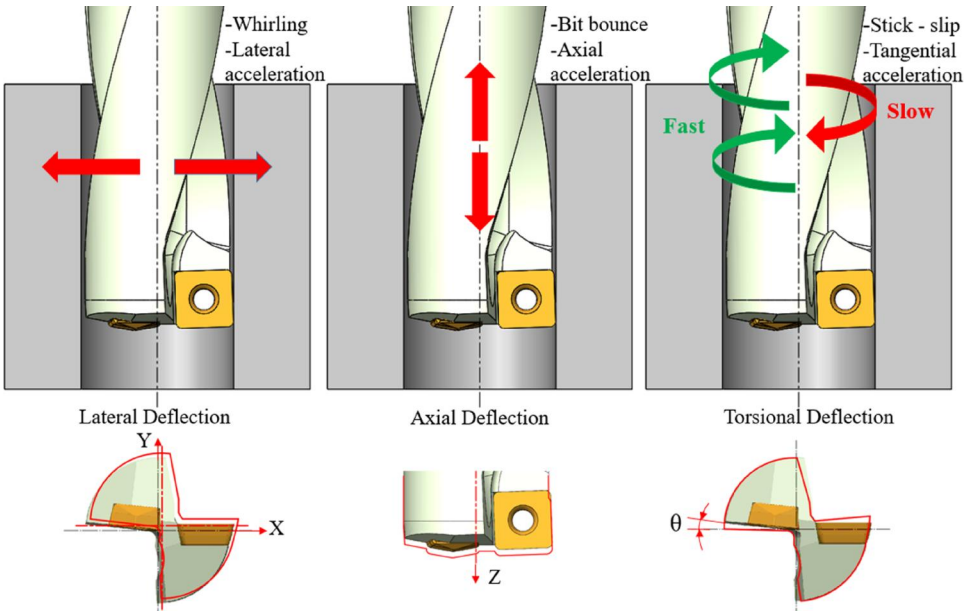


Figure 8. Tool deflections.

chatter occurring in all experiments conducted with Tool 3. Additionally, this extra coolant hole may have acted as a chip breaker and caused shorter chips to form. This extra coolant hole may have acted as a chip breaker, resulting in shorter chips. Shorter chips may be more easily evacuated out of the hole, improving hole quality. It is believed that by opening an additional coolant hole in the U drill body, excess space is created, which weakens the drill's stability and chip-breaking capability. With the deterioration of rigidity, axial deviation may have occurred due to torsional-axial vibration (Abele et al., 2007). Because chatter, which is a high-amplitude vibration, occurs with axial deviations (Ema and Marui, 2003). Chattering, chip evacuation, and long curly chips are common problems in drilling holes with U drills (Svensson, Andersson, and Andersson Lassila, 2022). In addition, chattering occurs in relatively soft workpieces (Astakhov, 2014). The chip images in Figure 9 clearly show chatter to be present. Axial deviations cause an increase and decrease in the feed rate of the cutter in a repetitive manner (Ahmadi and Altintas, 2013). This situation increases and decreases the cut chip thickness instantly. Because of this, the cutting forces increase and decrease momentarily, resulting in a wave-like surface at the hole's bottom (Ema and Marui, 2003). With the increase in the length/diameter ratio, lateral vibrations increased, causing an increase in the tolerance values for size and shape and worsening of the hole quality (Yaman, Bicakci, and Ozgedik, 2017). In Tool 3, high-amplitude chatter occurred instead of lateral vibrations. As the rigidity deteriorated, axial deviation may have occurred due to torsional-axial vibration (Abele et al., 2007). Insert and chip images confirm this. Thus, it is determined that it causes lower average surface roughness as well as lower size and shape tolerances. In addition, when the balance angle values in U drills are examined, the balance angle of Tool 3 is larger than that of Tool 2 and Tool 4. A higher balance angle improved the hole quality and resulted in lower values. The smallest balance angle was given to Tool 4 by the manufacturer.

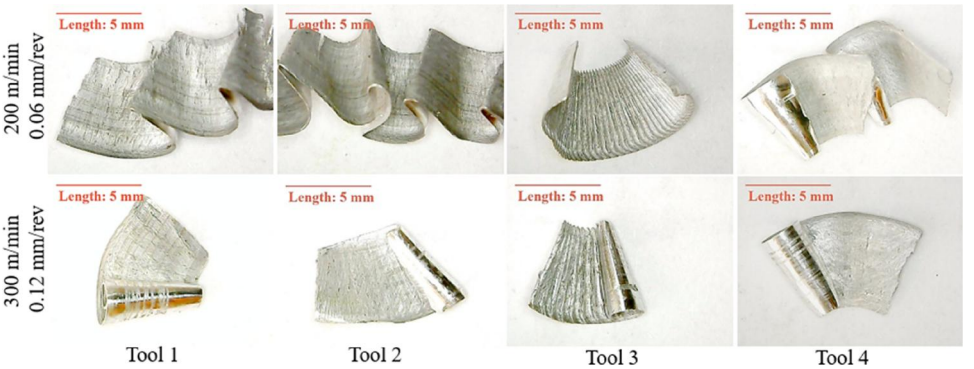


Figure 9. Chip images that occur.

With the increase in tool length, the lateral deviations increased more, and it was determined that worse hole quality occurred.

It can be said that chatter, which is a common problem in U drills, is dampened due to chips sticking or jamming in the chip evacuation channel (Parsian et al., 2017). Because no chatter marks were observed in the chip and insert images except for Tool 3. In Tool 3, it is difficult to talk about the vibration damping effect of the chips broken by the drilled hole and the extra coolant hole located close to the spindle axis. Because chatter marks on chips produced by Tool 3 are readily apparent in all feed rate and cutting speed combinations, improved hole quality was the result of the shorter chips being evacuated from the cutting media more quickly and easily (Uddin et al., 2018). However, when the hole quality was examined, the best output responses were obtained with Tool 3. It can be thought that the workpiece and clamping apparatus are not rigid, so that the vibrations increase, but when the chips, cutting-edge images, and force graphs are examined, it becomes difficult to talk about such a situation. Because chatter occurred in all drilling experiments with Tool 3, no chatter was observed in other U drills. Chatter is undesirable because it causes unbalanced forces, causing premature wear of the cutter.

Figure 10 shows the insert regions. These regions and geometric angles are different for the central and peripheral inserts. Therefore, it is normal for different dynamic phenomena to occur at the central and peripheral inserts (Svensson, Andersson, and Andersson Lassila, 2022). The region affected by the cutting along the cutting edge is apparent in accordance with the central and periphery inserts' flank surfaces in Figure 11. Cutting-edge images were produced by drilling experiments done at 300 m/min cutting speed and 0.12 mm/rev feed rate. When comparing the new insert with the used inserts, only the inserts obtained with Tool 3 showed a significant cut-affected zone (peripheral insert 0.19 mm, central insert 0.12 mm). The area affected by this section is thought to be caused by the chattering that occurs when drilling with Tool 3. Because chatter and vibrations in the torsional-axial direction increase, the load on the cutter increases and causes premature wear (Abele et al., 2007). This situation is

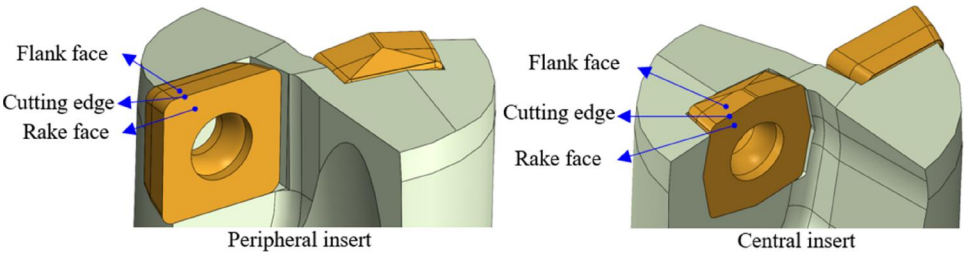


Figure 10. Insert regions.

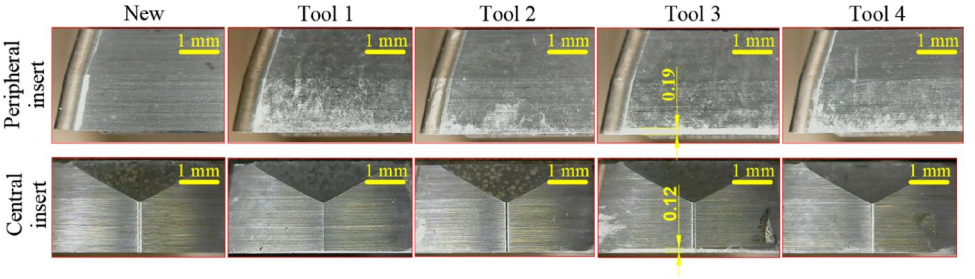


Figure 11. Insert flank surfaces (300 m/min – 0.12 mm/rev).

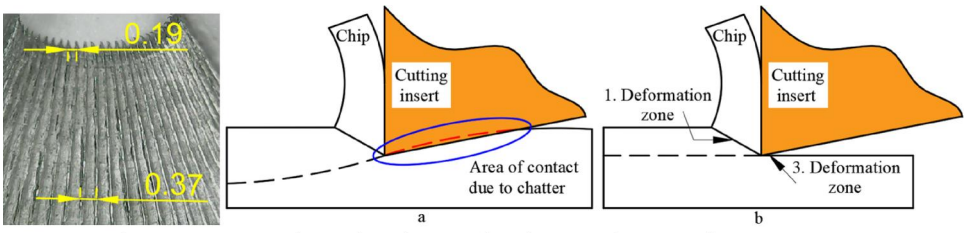


Figure 12. (a) There is chatter in the cut (b) No chatter on cut.

more clearly understood when we look at the diagram of the cutting process with chatter (Figure 12a) and without chatter (Figure 12b) in Figure 12. The chatter-induced wavy texture at the hole's bottom (Ema and Marui, 2003), caused significantly more friction on the cutting insert's flank surface in the third deformation zone. Since the subject is aluminum material and a new insert is used in each drilling test, no wear mechanism has occurred. The negative effect of chatter on the cutting inserts is clearly understood.

Power spectral density (PSD) is a term used to describe how a signal's power varies with frequency (Nieslony et al., 2016). Welch's method was applied in PSD to examine the effect of axial and lateral forces on machining dynamics and hole quality in drilling with U drills. Figure 13 schematically depicts the forces acting on the U drill and the region cut by each insert. The letters F_x and F_y, respectively, stand for the lateral forces operating on the x and y axes. M_z stands for the torque, while F_z stands for the thrust in the direction of the hole axis. Each insert cuts different parts of the hole according to the hole axis. Therefore, different dynamic loads occur on the inserts and affect the hole quality. The different features of the U drill bodies examined within the scope of the current study caused different output responses.

Figure 14 represents the movement of lateral forces with respect to time. Together with Tool 1, Tool 3 with the additional coolant hole produced more steady lateral forces at the hole's entrance. At the exit of the hole, sudden peaks occurred due to the smearing and/or adhesion of aluminum

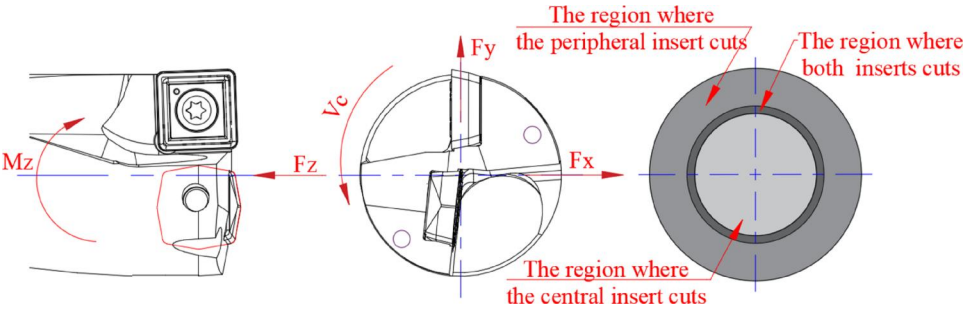


Figure 13. Forces acting on the U drill.

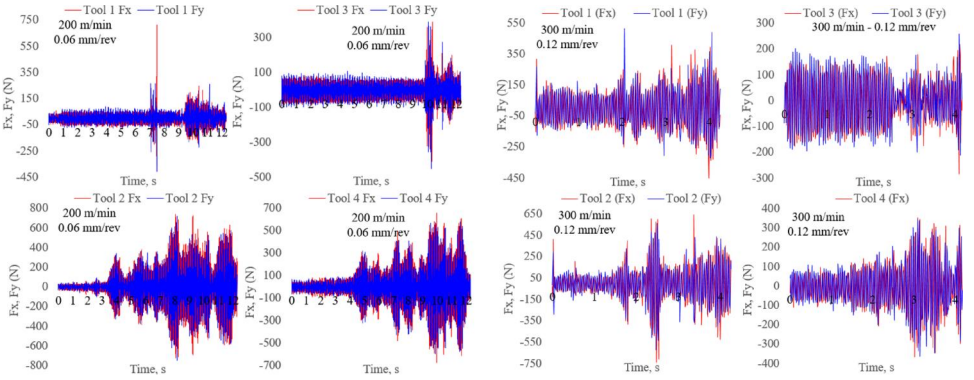


Figure 14. Lateral forces F_x, F_y in time domain.

materials to the cutter or chip evacuation problems. For Tool 2 and Tool 4, after a hole depth of approximately 10 mm, sudden increases in lateral forces due to increased chip adhesion and/or clogging and sudden decreases with the removal of chips occurred. These sudden peaks cause Tool deflection, causing grooves to form along the hole. It has been evaluated that these peaks increase with the compression of the chips and return to the normal level with their release. It can be said that the balance angle has a clear effect on these graphs. Because the graphs of Tools 1 (6.38°) and 3 (5.99°) are very similar, the graphs of Tools 2 (5.27°) and 4 (4.96°) are also very similar. It can be said that balance angles close to each other cause similar lateral deviations. Apart from that, it was evaluated that a higher balance angle causes fewer lateral forces and fewer sudden force peaks. With the change in the balance angle, the helical chip evacuation channel design also changes. Flute design and dimensions have a great influence and are important in removing chips from the hole without sticking or clogging (Parsian et al., 2017). The chip evacuation channel dimensions, where the central insert is located, also grow as the balance angle increases. This increase resulted in easier evacuation of chips cut by the central insert and less lateral deflection. However, there is a direct relationship between balance angle, drill length, helical flute design, and rigidity. In

order to obtain optimum output responses, optimal design parameters must be determined.

Figure 15 shows the evolution of the PSD function for lateral forces. According to the figure, when both F_x and F_y are taken into account, the dominant frequency value is 46.88 Hz in low cutting parameters (0.06 mm/rev and 200 m/min), while it is 20.7 Hz in high cutting parameters (0.12 mm/rev and 300 m/min). A higher increase in amplitude was seen at lower frequency values as drilling parameters were increased. In low-cutting parameters, Tools 2 and 4 created the highest amplitude values, while Tools 1 and 3 created the lowest amplitude values. Tool 2 produced the largest amplitude value under high cutting parameters, while Tool 3 produced the lowest amplitude values. PSD graphs also confirm the effect of the balance angle. Because the balance angles were close to each other, they caused the formation of amplitude values close to each other. Compared to low shear parameters, the effect of the balance angle decreased at high shear parameters, and the PSD signals became closer to each other. These results confirmed that the best hole quality was achieved with Tool 3.

Figure 16 shows the evolution of the PSD function for F_z and M_z. According to the figure, considering F_z for Tool 3, the dominant frequency

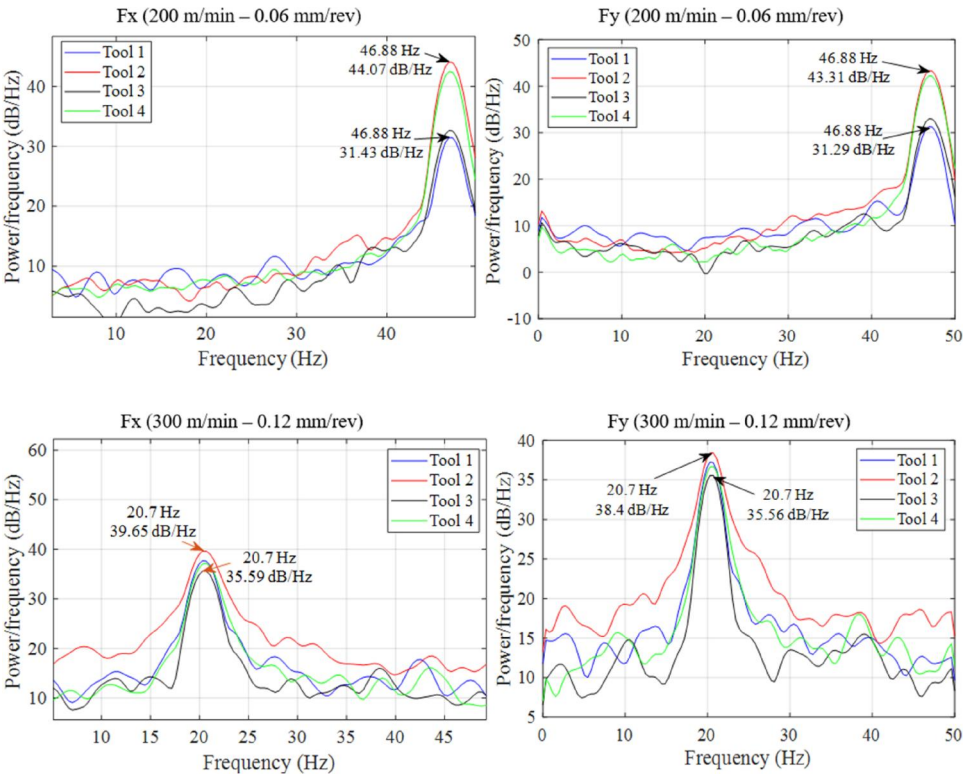


Figure 15. PSD of lateral forces F_x and F_y.

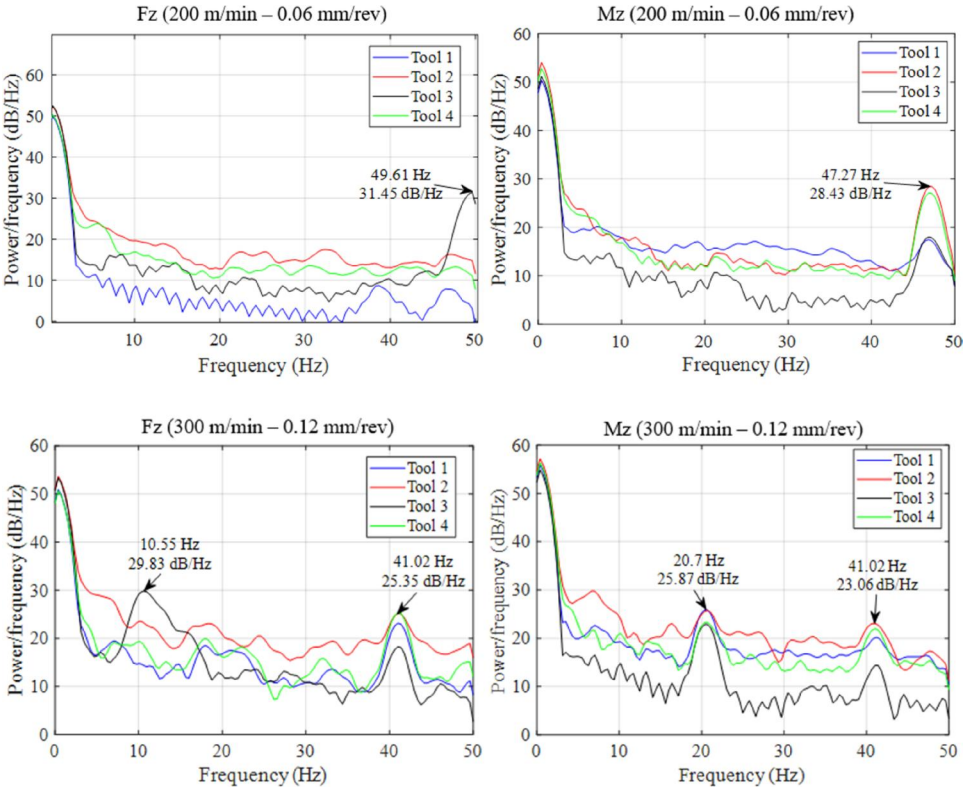


Figure 16. PSD of F_z and M_z.

was 49.61 Hz in low cutting parameters and 10.55 Hz in high cutting parameters. Other U drills did not show a significant peak at this frequency value. For Tool 3, it is like proof that vibrations occur in the direction of the hole axis. It is thought that the F_z forces that occur at this frequency value have a share in the occurrence of chatter in the chip images. According to estimates, Tool 3 differs from previous U drills due to a third coolant hole that was opened in the chip evacuation channel. While the larger balance angle in Tool 3 reflected positively on the lateral forces and hole quality, it caused higher thrust when it was coupled with the extra coolant hole. Higher thrust results in more power consumption, increased temperature, and increased contact at the tool/chip interface (Shah, Khanna, and Chetan, 2020; Liu et al., 2023). Thus, hole quality and inserts are adversely affected. When M_z is taken into account, 20.7 and 41.02 Hz in high cutting parameters of 47.27 Hz draw attention as the dominant frequency values in low cutting parameters. Tool 1 and Tool 3, which had the maximum balancing angle, produced the least amplitude values. The lowest amplitude values for M_z at low and high cutting parameters were obtained with Tool 3. The occurrence of lower and more stable M_z values reflected positively on the hole quality.

When the values obtained with Tool 3 are examined, imbalances in lateral forces and deviations from hole quality are minimal. The stability of chatter may have helped improve its quality. Because vibration movements in the axial direction may have resulted in the improvement of hole quality, as in the vibration-assisted drilling process, resulting in minimum values. Vibration-assisted drilling improves hole quality by reducing built-up edges and material sticking to the cutter (Guba et al., 2022). Although the hole quality is better, Tool 3 cannot be advised for the evaluated drilling parameters due to chatter and higher thrust forces that would result in quicker cutting edge wear and an increase in the machine's power consumption, which will raise the cost. However, it is determined that Tool 3 may be used under rigid conditions with no chatter by constructing stability lobe diagrams for the CNC and Tool 3.

Figure 17 shows the hole quality metrics measured with the CMM as a result of the drilling process using various U drills. Tool 1 and Tool 3 created lower diameter deviation values with the effect of a higher balance angle, while Tool 2 and Tool 4 created higher values with the effect of a lower balance angle. The balance angle did not make a significant difference in deviation from circularity or surface roughness. For all U drills, a better mean surface roughness was acquired at the hole's entrance, while a poorer mean surface roughness was at the hole's exit. The values at the end

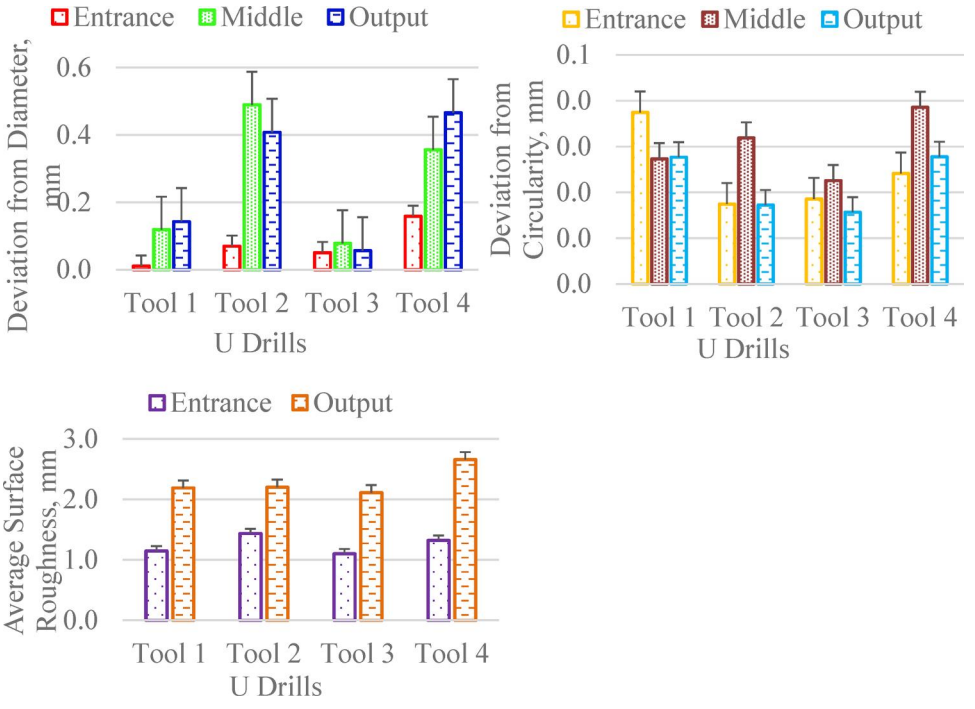


Figure 17. Variation of hole quality along hole depth.

of the hole were 91% higher for Tool 1, 45.8% higher for Tool 2, 92.3% higher for Tool 3, and 101% higher for Tool 4 compared to the entry of the hole. Adhesion of the material to the cutter is a big problem in the processing of aluminum (Al-Tameemi et al., 2021). With the increase in hole depth in operations such as drilling, chip clogging, and adhesion, and loads on the cutter can cause vibration (Khan et al., 2020). The increase in vibrations in the cutting tool negatively affects the hole roughness values (Wang, Venkatesh, and Xue, 1991). Thus, it was evaluated that the roughness values may have increased at the end of the hole (Venkatesh and Xue, 1996). More drill deviations occur as the hole depth rises (Yaman, Bicakci, and Ozgedik, 2017). However, according to the figure, the highest circularity deviation values for Tools 2, 3, and 4 occurred in the middle of the hole. The image in Figure 18 confirms this result. Adhesive aluminum chips tend to stick to the chip evacuation channels of the U drill (Biermann and Hartmann, 2012). It was thought that the lateral forces increased as a result of this adhesion. Thus, the highest lateral deviation occurred in the middle of the hole. This situation resulted in higher values by deteriorating the hole quality in the middle of the hole.

The inside view of a hole drilled with Tool 2 is shown in Figure 18. When this image is examined, the roughness measured at the entry of the hole is 2.96 µm, while the roughness measurement at the hole's exit is 4.24 µm. The aluminum material was stuck to the hole wall and the U drill's chip evacuation channel in the middle of the hole, giving it a rougher surface. The cut chips are in contact with the U drill body and the hole wall for a longer period of time as the hole depth rises. Additionally, as the hole depth increases, the coolant cannot penetrate the cutting medium sufficiently. Because aluminum is the material being processed, heat and friction cause the workpiece and chips to stick to the cutter. This situation causes an increase in lateral forces. It has a direct effect on the lateral forces in the stick slip resulting from the torsion of the U drill. It is

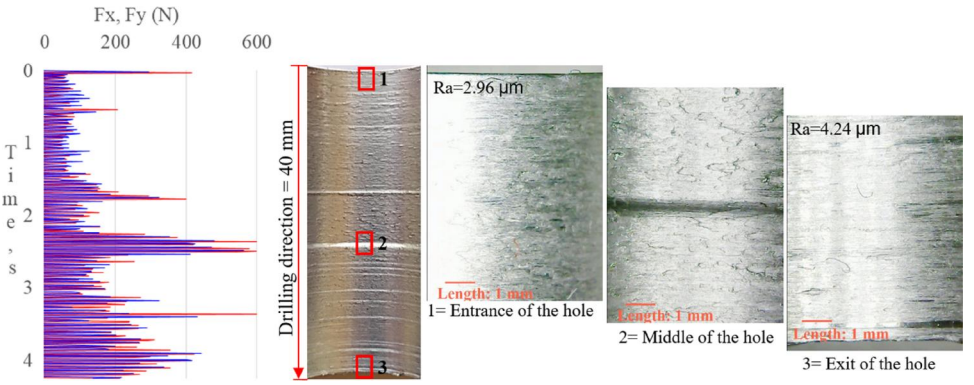


Figure 18. In-hole view (Tool 2–0.12 mm/rev–300 m/min).

predicted that higher lateral forces in long-term use will cause earlier wear of the cutter and deterioration in hole geometry and surface roughness. In fact, with the increase in smearing and chip clogging, tool deviation due to lateral forces increased considerably (Kurt, Kaynak, and Bagci, 2008), and a large hollow channel was formed with the effect of escaping chips. Toward the end of the hole, smaller but more frequent channels were formed. While the lateral force and the hole's surface quality are compared, it is evident that the surface quality is good when the lateral forces are low and that it degrades as the lateral forces increase. It is clear that the channels formed in the in-hole walls are correlated with the increase in lateral forces.

Feed rate's impact on hole quality

For each feed rate, separate trials were run at the three cutting speeds of 200, 250, and 300 m/min. Hole quality values were obtained according to the feed rate by taking the average of three cutting speeds (Figure 19). There was no linear association between the increase in feed rate and the deviation from the diameter when drilling aluminum alloys (Aamir et al., 2021). It is clear how the balance angle affects the deviation from the diameter. Because, as mentioned before, a higher balance angle caused lower diameter deviation values for Tools 1 and 3. According to the literature, deviation from circularity values increased with feed rate for all U drills

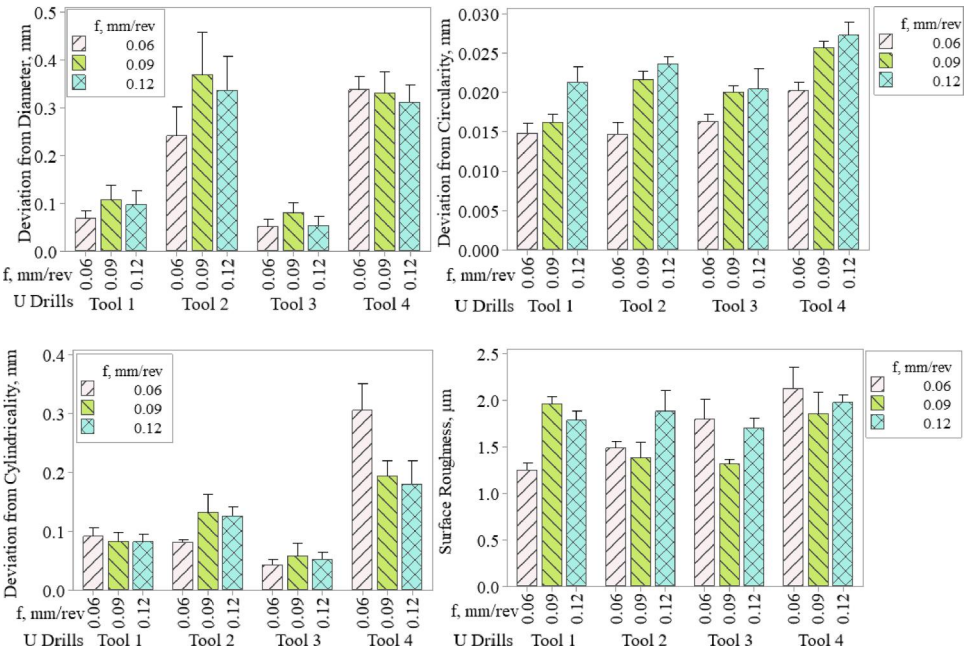


Figure 19. Change of average surface roughness according to U drill and f values.

(Zitoune, Krishnaraj, and Collombet, 2010). Values for U drills other than Tool 4 were quite close to each other. Deviation from cylindricality was quite high for Tool 4 due to the increase in tool length and lower balance angle. According to the literature, a boost in feed rate is accompanied by a corresponding elevation in mean surface roughness (Bahçe and Özdemir, 2019). However, a more ambiguous situation occurred in the present study. Chip adhesion and/or smearing to the chip evacuation channels of the U drill, the inserts, and the hole surface caused irregularities in the roughness values. In addition, as the hole's depth deepens, the cooler provided from the outside becomes insufficient, and the temperature rises, this outcome has happened, leading to more uneven material adherence to the surface (Aamir et al., 2021). For output responses other than diameter deviation, it is difficult to talk about the effect of the balance angle with respect to the feed rate. Because there was no discernible difference between U drills. It was determined that it would be appropriate to prefer a low or high feed rate. Selecting a higher feed rate may be preferred, as it will shorten the drilling time. There is no big difference between the values.

Effect of cutting speed on hole quality

Cutting speed directly affects hole quality (Martins et al., 2021). Separate experiments were carried out at three feed rates (0.06–0.09–0.12 m/min) for each cutting speed. Hole quality values were obtained according to

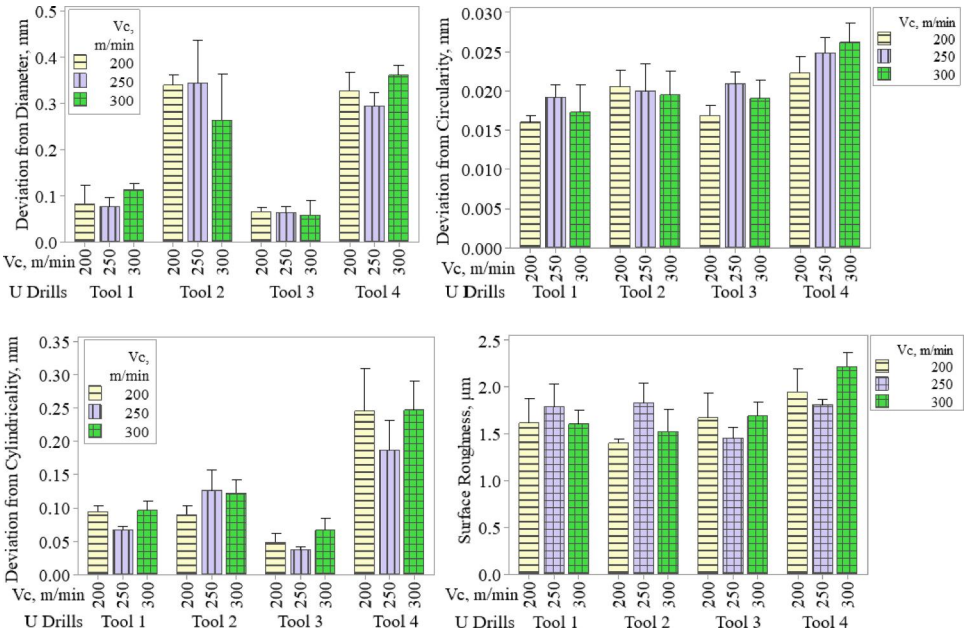


Figure 20. Variation of average surface roughness according to U drill and Vc values.

cutting speed by taking the mean of three feed rates (Figure 20). When the variation of the deviation from the diameter was examined according to the U drill and Vc values, lower values were obtained with Tool 1 and Tool 3. Higher values were obtained with Tools 2 and 4, where the balance angle was smaller. Deviation from circularity results in unstable drilling (Zitoune, Krishnaraj, and Collombet, 2010). In some studies, it is stated that spindle runout is more dominant at high *Vc* values (Harshith, Devendra, and Jagadesh, 2019), while in other studies, it is argued that tool runout decreases with increasing spindle speed (Bahçe and Özdemir, 2019). For aluminum alloys, any increase in speed results in aluminum adhesion to the drill (Harshith, Devendra, and Jagadesh, 2019). Adhesion negatively affects hole quality and causes irregular responses (Al-Tameemi et al., 2021). In the measurement with the CMM after the drilling of aluminum alloys, the debris adhering to the inner surface of the hole may come into contact with the measurement probe and cause erroneous results (Uddin et al., 2018). The roughness values fluctuated ash the cutting speed rose (Zitoune, Krishnaraj, and Collombet, 2010). Roughness is said to improve up to a level with increasing cutting speed but then worsen (Committee). In addition, there are increases and decreases according to the cutting speed in various studies (Kilickap and Hüseyinoglu, 2009). In aluminum, the drilling time decreases when the cutting speed rises. The texture of the machined hole is scraped, and the drilling media chips cling to it. In this situation, the cut chips may smear or stick to the interior of the hole, lowering the roughness values (Rahman, Seah, and Venkatesh, 1988). In the present study, no linear relationship between hole quality and cutting speed was observed when drilling with a U drill. Choosing a low or high cutting speed does not cause significant differences in hole quality.

Conclusion

In this study, AA 7075-T651 material was drilled to a depth of 40 mm using four different. Forces were measured with a dynamometer during hole drilling; diameter deviation, circularity deviation, and cylindricity deviation values were measured with a CMM machine after drilling; and average surface roughness values were measured with a roughness measuring device. Various findings were obtained by interpreting the measurement according to the U drill findings, length/diameter ratio, cutting speed, and feed rate.

In comparison to the tool without it, the tool with a third coolant hole introduced into the chip evacuation channel near the center insert provided lower results for diameter deviation, circularity deviation, cylindricity deviation, and average surface roughness. Even though the drilling experiments

employed by the U drill with the extra coolant hole had superior hole quality, they also had higher thrust force and noise. With the chatter, more cutting-affected areas occurred on the cutting inserts. Therefore, it was evaluated that tool life would decrease after more drilling repetitions. The average roughness of the surface was greater near the hole's entrance than at its exit. When lateral forces and inside-hole surface quality are compared, roughness values are low in places where lateral forces are small, while roughness values are high in places where lateral forces are high. Channels formed within the hole where there were sudden peaks in the lateral force signals. It has been evaluated that this situation is achieved as a result of the adhesion or plastering of the aluminum material due to the increasing lateral forces as the hole depth increases. While the feed rate increase was accompanied by an increase in the deviation from circularity values for all U drills, other output responses revealed an unstable condition. While higher balance angles have a positive effect on hole quality, lower balance angles have a negative effect. Therefore, it was decided that opening a third cooler hole in the chip evacuation route, which is where the inner insert resides, was not necessary.

Future works

This study intends to examine the impact on hole quality of indexable drilling AA 7075-T651 material with various U drills. Since the tool length has no influence, it was believed that evaluating the effect of the balance angle on the hole quality with U drills that had the same nominal diameter and L/D ratio would produce more accurate results. However, due to market conditions and experimental possibilities limitations, it could not be examined in this study. It is thought that the results of this research, which will affect the production and design of U drills in the future, will form the basis for further studies. It is planned to examine this issue in future studies. Future work can be listed as follows:

- Performances in internal cooling, external cooling, cryogenic cooling, and dry conditions can be compared with material groups other than aluminum.
- To compare U drills, output responses such as cutting forces, vibration, sound, and hole quality can be examined.
- Stability lobe diagrams can be produced for U drills.
- How changing the coating, material, balance angles, channel design, and cutting insert positions of U drills affects the output responses can be examined.

Nomenclature

CNC	Computer numerical control
AA	Aluminum alloy
AISI	American iron and steel institute
ANFIS	Adaptive neuro-fuzzy inference system
GRA	Gray relational analysis
ANN	Artificial neural networks
L/D	Length/diameter ratio
Fx	Lateral force on the *x*-axis, *N*
Fy	Lateral force on the *y*-axis, *N*
Fz	Thrust force, *N*
f	Feed rate, mm/rev
Mz	Torque, Ncm
Vc	Cutting speed, m/min
D	Diameter, mm
L	Length, mm
θ	Angular deviation
CMM	Computer measuring machine
PSD	Power spectral density

Acknowledgments

The BAP department at Gazi University is thanked by the researchers for their assistance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

It was funded by the Scientific Research Projects Unit of Gazi University under grant number 07/2019-08.

ORCID

Aslan Akdulum http://orcid.org/0000-0003-2030-3167
Yunus Kayir http://orcid.org/0000-0001-6793-7103

References

Aamir, M.; Tolouei-Rad, M.; Giasin, K.; Vafadar, A.; Koklu, U.; Keeble, W. (2021). Evaluation of the surface defects and dimensional tolerances in multi-hole drilling of AA5083, AA6061, and AA2024. *Applied Sciences*, 11(9): 4285. doi:10.3390/app11094285.

Abele, E.; Ellermeier, A.; Hohenstein, J.; Tschannerl, M. (2007) Tool length influence on wear behaviour of twisted carbide drills. *Production Engineering*, 1(1): 51–56. doi:10.1007/s11740-007-0029-5.

Abele, E.; Schäfer, D. (2013) A new approach for a simulation-based prediction of torsional chatter in deep hole drilling with extra-long twist drills. *International Manufacturing Science and Engineering Conference*, American Society of Mechanical Engineers. doi:10.1115/MSEC2013-1184.

Ahmadi, K.; Altintas, Y. (2013) Stability of lateral, torsional and axial vibrations in drilling. *International Journal of Machine Tools and Manufacture*, 68: 63–74. doi:10.1016/j.ijmachtools.2013.01.006.

Ahmed, L.S.; Kumar, M.P. (2016) Cryogenic drilling of Ti–6Al–4V alloy under liquid nitrogen cooling. *Materials and Manufacturing Processes*, 31(7): 951–959. doi:10.1080/10426914.2015.1048475.

Akdulum, A.; Kayir, Y. (2023a) Experimental investigation and optimization of process stability in drilling of Al 7075-T651 using indexable insert drills. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 45(8): 429. doi:10.1007/s40430-023-04303-w.

Akdulum, A.; Kayir, Y. (2023b) Investigation of the effect of u drills with different properties on thrust force, torque and spindle load. *Politeknik Dergisi*, 26(1): 387–400. doi:10.2339/politeknik.1113301.

Akdulum, A.; Kayir, Y. (2023c) Modeling and estimation of thrust force, torque, and surface roughness in indexable drilling of AA6061-T651 with Taguchi, ANN, and ANFIS. *Sādhanā*, 48(3): 143. doi:10.1007/s12046-023-02209-w.

Al-Tameemi, H.A.; Al-Dulaimi, T.; Awe, M.O.; Sharma, S.; Pimenov, D.Y.; Koklu, U.; Giasin, K. (2021) Evaluation of cutting-tool coating on the surface roughness and hole dimensional tolerances during drilling of Al6061-T651 alloy. *Materials (Basel, Switzerland)*, 14(7): 1783. doi:10.3390/ma14071783.

Arvajeh, T.; Ismail, F. (2006) Machining stability in high-speed drilling—Part 1: Modeling vibration stability in bending. *International Journal of Machine Tools and Manufacture*, 46(12-13): 1563–1572. doi:10.1016/j.ijmachtools.2005.09.018.

Astakhov, V.P. (2014) *Drills: Science and Technology of Advanced Operations*. CRC Press.

Aydin, B.; Ozcatalbas, Y. (2003) AA2014 (T6) Alaşımının İşlenebilirlik Özelliklerine Kesici Takım Geometrisinin Etkisi. *Makina Tasarım ve İmalat Dergisi*, 5(2): 89–95.

Bahçe, E.; Özdemir, B. (2019) Determination of tool deflection in drilling by image processing. *IET Image Processing*, 13(13): 2487–2494. doi:10.1049/iet-ipr.2019.0267.

Bayraktar, Ş; Çamkerten, Ç. (2020) Al-25Zn-3Cu-3Si Alaşımının İşlenmesinde Kaplamasız ve CVD-TiCN Kaplamalı Kesici Uçların Kesme Performansının Karşılaştırılması. *Uluslararası Mühendislik Araştırma ve Geliştirme Dergisi*, 12(2): 618–623. doi:10.29137/umagd.705125.

Biermann, D.; Hartmann, H. (2012) Reduction of burr formation in drilling using cryogenic process cooling. *Procedia CIRP*, 3: 85–90. doi:10.1016/j.procir.2012.07.016.

ASM International Handbook Committee. (1992) Properties and selection: nonferrous alloys and special-purpose materials. *ASM international*, 2: 1143–1144. doi:10.31399/asm.hb.v02.9781627081627.

Ema, S.; Marui, E. (2003) Theoretical analysis on chatter vibration in drilling and its suppression. *Journal of Materials Processing Technology*, 138(1–3): 572–578. doi:10.1016/S0924-0136(03)00148-1.

Giasin, K.; Hodzic, A.; Phadnis, V.; Ayvar-Soberanis, S. (2016) Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study. *The International Journal of Advanced Manufacturing Technology*, 87(5-8): 2041–2061. doi:10.1007/s00170-016-8563-y.

Guba, N.; Schumski, L.; Paulsen, T.; Karpuschewski, B. (2022) Vibration-assisted deep hole drilling of the aluminum material AlMgSi0. 5. *CIRP Journal of Manufacturing Science and Technology*, 36: 57–66. doi:10.1016/j.cirpj.2021.11.002.

Harshith, N.; Devendra, Y.; Jagadesh, T. (2019) Investigations into surface integrity and cylindricity error during peck drilling of aerospace alloy using graphite, MOS2 and blasocut lubricant. *Materials Today: Proceedings*, 18: 3091–3098. doi:10.1016/j.matpr.2019.07.182.

Heisel, U.; Schaal, M. (2009) Burr formation in short hole drilling with minimum quantity lubrication. *Production Engineering*, 3(2): 157–163. doi:10.1007/s11740-009-0153-5.

Jochem, C. (2006) () Mechanics and dynamics of drilling, Ph. D. thesis, Faculty of Applied Science, University British Columbia.

Kaymakci, M.; Kilic, Z.; Altintas, Y. (2012) Unified cutting force model for turning, boring, drilling and milling operations. *International Journal of Machine Tools and Manufacture*, 54-55: 34–45. doi:10.1016/j.ijmachtools.2011.12.008.

Khan, S.A.; Shamail, S.; Anwar, S.; Hussain, A.; Ahmad, S.; Saleh, M. (2020) Wear performance of surface treated drills in high speed drilling of AISI 304 stainless steel. *Journal of Manufacturing Processes*, 58: 223–235. doi:10.1016/j.jmapro.2020.08.022.

Kilic, Z.; Altintas, Y. (2016) Generalized mechanics and dynamics of metal cutting operations for unified simulations. *International Journal of Machine Tools and Manufacture*, 104: 1–13. doi:10.1016/j.ijmachtools.2016.01.006.

Kilickap, E.; Hüseyinoglu, M. (2009) Effect of coolant technique on performance characteristic in drilling of 7075 aluminum alloy. *Engineering Sciences*, 4(4): 547–558.

Kurt, M.; Kaynak, Y.; Bagci, E. (2008) Evaluation of drilled hole quality in Al 2024 alloy. *The International Journal of Advanced Manufacturing Technology*, 37(11-12): 1051–1060. doi:10.1007/s00170-007-1049-1.

Li, S.; Zhang, D.; Liu, C.; Tang, H. (2020) Exit burr height mechanistic modeling and experimental validation for low-frequency vibration-assisted drilling of aluminum 7075-T6 alloy. *Journal of Manufacturing Processes*, 56: 350–361. doi:10.1016/j.jmapro.2020.04.083.

Liu, Y.; Geng, D.; Zhang, D.; Zhai, Y.; Liu, L.; Sun, Z.; Shao, Z.; Zhang, M.; Jiang, X. (2023) Cutting performance and surface integrity for rotary ultrasonic elliptical milling of Inconel 718 with the ball end milling cutter. *Journal of Materials Processing Technology*, 319: 118094. doi:10.1016/j.jmatprotec.2023.118094.

Martins, P.S.; Carneiro, J.R.G.; Ba, E.C.T.; Vieira, V.F. (2021) Study on roughness and form errors linked with tool wear in the drilling process of an Al-Si alloy under high cutting speed using coated diamond-like carbon high-speed steel drill bits. *Journal of Manufacturing Processes*, 62: 711–719. doi:10.1016/j.jmapro.2021.01.006.

Nieslony, P.; Cichosz, P.; Krolczyk, G.; Legutko, S.; Smyczek, D.; Kolodziej, M. (2016) Experimental studies of the cutting force and surface morphology of explosively clad Ti–steel plates. *Measurement*, 78: 129–137. doi:10.1016/j.measurement.2015.10.005.

Nieslony, P.; Krolczyk, G.; Zak, K.; Maruda, R.; Legutko, S. (2017) Comparative assessment of the mechanical and electromagnetic surfaces of explosively clad Ti–steel plates after drilling process. *Precision Engineering*, 47: 104–110. doi:10.1016/j.precisioneng.2016.07.011.

Nouari, M.; List, G.; Girot, F. A.; Gehin, D. (2005) Effect of machining parameters and coating on wear mechanisms in dry drilling of aluminium alloys. *International Journal of Machine Tools and Manufacture*, 45(12–13): 1436–1442. doi:10.1016/j.ijmachtools.2005.01.026

Okada, M.; Asakawa, N.; Sentoku, E.; M'Saoubi, R.; Ueda, T. (2014) Cutting performance of an indexable insert drill for difficult-to-cut materials under supplied oil mist. *The International Journal of Advanced Manufacturing Technology*, 72(1–4): 475–485. doi:10.1007/s00170-014-5691-0.

Paktinat, H.; Amini, S. (2017) Ultrasonic assistance in drilling: FEM analysis and experimental approaches. *The International Journal of Advanced Manufacturing Technology*, 92(5-8): 2653–2665. doi:10.1007/s00170-017-0285-2.

Parsian, A. (2018) *Regenerative Chatter Vibration in Indexable Drills: Modeling and Simulation*. University West.

Parsian, A.; Magnevall, M.; Beno, T.; Eynian, M. (2017) Sound analysis in drilling, frequency and time domains. *Procedia CIRP*, 58: 411–415. doi:10.1016/j.procir.2017.03.242.

Rahman, M.; Seah, K.; Venkatesh, V. (1988) Performance evaluation of endrills. *International Journal of Machine Tools and Manufacture*, 28(4): 341–349. doi:10.1016/0890-6955(88)90048-X.

Ralph, W.C.; Johnson, W.S.; Toivonen, P.; Makeev, A.; Newman Jr, J. (2006) Effect of various aircraft production drilling procedures on hole quality. *International Journal of Fatigue*, 28(8): 943–950. doi:10.1016/j.ijfatigue.2005.09.009.

Sekmen, M.; Günay, M.; Şeker, U. (2015) Alüminyum alaşımlarının işlenmesinde kesme hızı ve talaş açısının yüzey pürüzlülüğü, yığıntı talaş ve yığıntı katmanı oluşumu üzerine etkisi. *Politeknik Dergisi*, 18(3): 141–148. doi:10.2339/2015.18.3141-148.

Shah, P.; Khanna, N.; Chetan. (2020) Comprehensive machining analysis to establish cryogenic LN2 and LCO2 as sustainable cooling and lubrication techniques. *Tribology International*, 148: 106314. doi:10.1016/j.triboint.2020.106314.

Sheth, S.; George, P. (2016) Experimental investigation, prediction and optimization of cylindricity and perpendicularity during drilling of WCB material using grey relational analysis. *Precision Engineering*, 45: 33–43. doi:10.1016/j.precisioneng.2016.01.002

Sun, Z.; Geng, D.; Meng, F.; Zhou, L.; Jiang, X.; Zhang, D. (2023) High performance drilling of T800 CFRP composites by combining ultrasonic vibration and optimized drill structure. *Ultrasonics*, 134: 107097. doi:10.1016/j.ultras.2023.107097.

Svensson, D.; Andersson, T.; Andersson Lassila, A. (2022) Coupled Eulerian–Lagrangian simulation and experimental investigation of indexable drilling. *The International Journal of Advanced Manufacturing Technology*, 121(1–2): 471–486. doi:10.1007/s00170-022-09275-0.

Totten, G.E.; MacKenzie, D.S. (2003) *Handbook of Aluminum: Vol. 1: Physical Metallurgy and Processes*. CRC Press.

Uddin, M.; Basak, A.; Pramanik, A.; Singh, S.; Krolczyk, G.M.; Prakash, C. (2018) Evaluating hole quality in drilling of Al 6061 alloys. *Materials (Basel, Switzerland)*, 11(12): 2443. doi:10.3390/ma11122443.

Varatharajulu, M.; Shahithya, R.; Jayaprakash, G.; Baskar, N.; Davim, J.P. (2021) Evaluation of desirability function approach and grey relation analysis for modeling circularity, perpendicularity and cylindricity in drilling magnesium AZ31. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 235(2): 238–248. doi:10.1177/0954408920952753.

Venkatesh, V.; Xue, W. (1996) A study of the built-up edge in drilling with indexable coated carbide inserts. *Journal of Materials Processing Technology*, 58(4): 379–384. doi:10.1016/0924-0136(95)02211-2.

Wang, S.; Venkatesh, V.; Xue, W. (1991) A study on modification of endrills for finishing holes. *Journal of Materials Processing Technology*, 28(1-2): 83–92. doi:10.1016/0924-0136(91)90208-V.

Xiang, J.; Xie, L.; Gao, F.; Yi, J.; Pang, S.; Wang, X. (2018) Diamond tools wear in drilling of SiCp/Al matrix composites containing copper. *Ceramics International*, 44(5): 5341–5351. doi:10.1016/j.ceramint.2017.12.154.

Yagmur, S.; Muharrem, P. (2021) Ti-6Al-4V Titanyum Alaşımının Delinmesinde Ön Delik Uygulamasının İşlenebilirliğe Etkisinin İncelenmesi. *International Journal of Engineering Research and Development*, 13(1): 170–177. doi:10.29137/umagd.771235.

Yaman, K.; Bicakci, N.; Ozgedik, A. (2017a) Investigation of the drill length effect on hole tolerances. *Journal of Polytechnic*, 20(4): 765–775. doi:10.2339/politeknik.368982.

Yaman, K.; Bicakci, N.; Ozgedik, A. (2017b) Matkap boyunun delik toleranslarına etkisinin incelenmesi. *Politeknik Dergisi*, 20(4): 765–775. doi:10.2339/politeknik.368982.

Yaşar, N. (2019) Thrust force modelling and surface roughness optimization in drilling of AA-7075: FEM and GRA. *Journal of Mechanical Science and Technology*, 33(10): 4771–4781. doi:10.1007/s12206-019-0918-5.

Zhu, Z.; Guo, K.; Sun, J.; Li, J.; Liu, Y.; Zheng, Y.; Chen, L. (2018) Evaluation of novel tool geometries in dry drilling aluminium 2024-T351/titanium Ti6Al4V stack. *Journal of Materials Processing Technology*, 259: 270–281. doi:10.1016/j.jmatprotec.2018.04.044.

Zitoune, R.; Krishnaraj, V.; Collombet, F. (2010) Study of drilling of composite material and aluminium stack. *Composite Structures*, 92(5): 1246–1255. doi:10.1016/j.compstruct.2009.10.010.